TOPOLOGY OPTIMIZATION AND EFFICIENCY ENHANCEMENT OF A BIDIRECTIONAL NON-ISOLATED DC–DC CONVERTER FOR DC-COUPLED RENEWABLE SYSTEMS

Shweta Maurya[1], **Dr. Imran Khan**[2]

[1]*Master of Technology, Electrical Engineering, Azad Institute of Engineering and Technology, Lucknow, India*
[2]*Professor, Department Electrical Engineering, Azad Institute of Engineering and Technology, Lucknow, India*

***

Abstract - *The rapid integration of renewable energy sources and battery storage systems has accelerated the adoption of DC-coupled architectures, where efficient power conversion plays a critical role in overall system performance. Bidirectional non-isolated DC–DC converters are key components in such systems, enabling controlled power flow between energy sources and storage units. However, conventional converter topologies often suffer from efficiency degradation due to switching losses, conduction losses, and suboptimal design under varying operating conditions. This paper presents a topology optimization and efficiency enhancement approach for a bidirectional non-isolated DC–DC converter tailored for DC-coupled renewable energy systems. The proposed method integrates advanced techniques such as interleaving, synchronous rectification, and soft-switching to minimize losses and improve performance in both buck and boost modes. A comprehensive mathematical model of the converter is developed, followed by simulation-based optimization using MATLAB/Simulink. The performance of the proposed topology is evaluated under different load and voltage conditions and compared with a conventional converter. Results demonstrate a significant improvement in efficiency, reduced voltage ripple, and enhanced dynamic response. The optimized converter achieves higher energy conversion efficiency across a wide operating range, making it suitable for photovoltaic-battery integrated systems and DC microgrid applications.*

Key Words: Bidirectional DC–DC Converter, DC Microgrid, Topology Optimization, Efficiency Enhancement, Renewable Energy Systems

1. INTRODUCTION

The transition toward sustainable energy systems has significantly transformed modern power networks, driven by the increasing integration of renewable energy sources and advanced energy storage technologies. Conventional centralized power systems are gradually being replaced by decentralized architectures that require efficient power conversion and control mechanisms. In this context, bidirectional DC–DC converters play a crucial role in enabling efficient energy exchange between generation sources, storage systems, and loads. The performance of these converters directly impacts the overall efficiency, reliability, and stability of DC-based renewable energy systems.

1.1 Background and Motivation

The global expansion of renewable energy systems, particularly solar photovoltaic (PV) and battery energy storage systems, has reshaped the structure of electrical power systems. Solar PV systems generate direct current (DC) power, while batteries inherently store energy in DC form, making them naturally compatible with DC-based infrastructures. The increasing deployment of PV–battery integrated systems has necessitated efficient power electronic interfaces to manage energy flow and ensure optimal utilization of available resources (Lund et al., 2015).

In recent years, there has been a noticeable shift from traditional AC-coupled architectures to DC-coupled systems. Unlike AC systems, which require multiple conversion stages (DC–AC–DC), DC-coupled architectures enable direct integration of renewable sources and storage units through a common DC bus. This reduces conversion losses, simplifies control, and improves overall system efficiency. Such systems are particularly advantageous in applications such as DC microgrids, electric vehicles, and data centers, where DC loads are predominant (Dragicevic et al., 2016).

Power converters serve as the backbone of these systems by facilitating voltage regulation, power flow control, and system stability. Bidirectional DC–DC converters, in particular, enable energy exchange between PV systems and batteries, allowing efficient charging and discharging operations. Their role is critical in maintaining energy balance, improving system flexibility, and ensuring reliable operation under varying generation and load conditions (Blaabjerg et al., 2017).

1.2 Problem Statement

Despite their advantages, bidirectional non-isolated DC–DC converters face several technical challenges that limit their performance in practical applications. One of the major issues is efficiency degradation caused by switching and conduction losses. Switching losses occur during the transition of semiconductor devices between ON and OFF states, while conduction losses arise due to the inherent resistance of components. These losses become more significant at higher switching frequencies and load conditions, reducing overall system efficiency (Erickson and Maksimović, 2001).

Another critical challenge is the asymmetrical performance of converters during bidirectional operation. In practical systems, converters operate in both buck (charging) and boost (discharging) modes. However, achieving high efficiency in both modes simultaneously is difficult due to differences in current paths, switching behavior, and component stress. This results in uneven performance and reduced reliability in dynamic operating environments (Khaligh and D'Antonio, 2010).

Furthermore, existing converter topologies are often not optimized for DC microgrid applications, where voltage levels vary significantly due to renewable intermittency and battery state-of-charge variations. Conventional designs may exhibit high ripple, increased losses, and limited voltage gain under such conditions. Therefore, there is a strong need for developing optimized converter topologies that can deliver high efficiency, reduced losses, and stable operation across a wide range of operating conditions.

1.3 Research Objectives

The primary objective of this research is to design and develop an optimized bidirectional non-isolated DC–DC converter suitable for DC-coupled renewable energy systems. The focus is on improving converter performance by addressing key limitations in existing topologies and enhancing overall energy conversion efficiency.

To achieve this, the study aims to incorporate advanced efficiency enhancement techniques such as soft-switching, synchronous rectification, and interleaving. These techniques help in minimizing switching and conduction losses, reducing thermal stress, and improving power density. By integrating these methods into the converter design, the research seeks to achieve superior performance compared to conventional approaches (Mohan, Undeland and Robbins, 2003).

Another important objective is to evaluate the performance of the proposed converter under dynamic operating conditions, including load variations and fluctuating input voltage typical of renewable energy systems. This ensures that the converter maintains stability, efficiency, and reliability in real-world applications. Through simulation and analytical modeling, the study aims to validate the effectiveness of the optimized topology and demonstrate its suitability for modern DC microgrid environments.

2. LITERATURE REVIEW

The literature on DC–DC converters and their application in renewable energy systems highlights continuous advancements in topology design, control strategies, and efficiency improvement techniques. With the increasing penetration of DC-based renewable systems, research has focused on improving converter performance, reducing losses, and enhancing dynamic response. This section reviews the fundamental concepts, commonly used topologies, efficiency enhancement methods, and control strategies relevant to bidirectional non-isolated DC–DC converters.

2.1 Overview of DC–DC Converters

DC–DC converters are essential power electronic devices used to convert one level of DC voltage to another while maintaining high efficiency and reliability. They operate based on high-frequency switching principles using semiconductor devices and energy storage elements such as inductors and capacitors. The fundamental operation involves controlling the duty cycle of switching signals to regulate output voltage, enabling both step-down (buck) and step-up (boost) functionalities. These converters are widely used in applications such as renewable energy systems, electric vehicles, and power supplies due to their high efficiency compared to linear regulators (Erickson and Maksimović, 2001).

DC–DC converters can be broadly classified based on isolation (isolated vs non-isolated), direction of power flow (unidirectional vs bidirectional), and switching techniques (hard-switching vs soft-switching). Among these, bidirectional converters have gained significant importance in modern energy systems as they enable controlled energy flow between sources and storage devices. Applications of bidirectional converters include battery energy storage systems, electric vehicles, and DC microgrids, where efficient charging and discharging operations are required. Their ability to operate in both buck and boost modes makes them highly suitable for systems with dynamic energy requirements (Khaligh and D'Antonio, 2010).

2.2 Review of Bidirectional Non-Isolated Topologies

Bidirectional non-isolated DC–DC converter topologies have been extensively studied due to their simplicity, compact design, and high efficiency in low-to-medium voltage applications. Among the conventional topologies, the buck–boost converter is widely used because of its ability to perform both step-up and step-down voltage conversion using a simple structure. However, it suffers from high current ripple and increased voltage stress on components, which can limit its performance in high-power applications.

To overcome these limitations, alternative topologies such as SEPIC (Single-Ended Primary Inductor Converter) and Ćuk converters have been developed. These converters provide continuous input and output current, reduced ripple, and improved voltage regulation compared to the basic buck–boost configuration. Despite these advantages, they involve higher component count and increased complexity, which may affect cost and implementation feasibility (Mohan, Undeland and Robbins, 2003).

Advanced topologies such as interleaved and multi-phase converters have gained attention for high-performance applications. Interleaved converters utilize multiple parallel phases operating with phase-shifted switching signals, resulting in reduced current ripple, improved thermal distribution, and enhanced efficiency. Multi-phase converters extend this concept to handle higher power levels with better dynamic response and reliability. These topologies are particularly suitable for renewable energy systems where high efficiency and power density are critical requirements (Blaabjerg et al., 2017).

2.3 Efficiency Enhancement Techniques

Improving the efficiency of DC–DC converters is a major focus in power electronics research, as energy losses directly impact system performance and operational cost. One of the most effective approaches to reducing switching losses is the implementation of soft-switching techniques such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). These methods ensure that switching transitions occur under zero voltage or zero current conditions, minimizing energy dissipation and reducing stress on semiconductor devices. Soft-switching is particularly beneficial in high-frequency applications, where switching losses are more pronounced (Zhang et al., 2014).

Synchronous rectification is another widely adopted technique for improving efficiency, especially in low-voltage, high-current applications. In this approach, conventional diodes are replaced with actively controlled MOSFETs, which have significantly lower conduction losses due to reduce on-state resistance. This results in improved efficiency and reduced heat generation within the converter.

Interleaving is also an important technique used to enhance converter performance. By operating multiple converter phases in parallel with phase-shifted switching, interleaving reduces input and output current ripple, improves thermal performance, and increases power density. The combination of these efficiency enhancement techniques enables significant improvement in overall converter performance, making them suitable for modern renewable energy systems.

2.4 Control Strategies

Control strategies play a vital role in ensuring stable operation, efficient power flow, and fast dynamic response of bidirectional DC–DC converters. Conventional control methods such as Pulse Width Modulation (PWM) and current mode control are widely used due to their simplicity and ease of implementation. PWM control regulates output voltage by adjusting the duty cycle of switching signals, while current mode control enhances system stability by incorporating current feedback, resulting in improved transient response and reduced sensitivity to parameter variations (Middlebrook and Ćuk, 1976).

In addition to conventional methods, advanced control strategies have been developed to address the limitations of linear control techniques in nonlinear and dynamic systems. Model Predictive Control (MPC) is one such approach that uses a mathematical model of the system to predict future behavior and optimize control actions accordingly. It offers superior dynamic performance and the ability to handle system constraints but requires higher computational resources.

Sliding Mode Control (SMC) is another advanced nonlinear control technique known for its robustness against parameter variations and external disturbances. It ensures fast response and stability by forcing the system to operate along a predefined trajectory. However, issues such as chattering need to be carefully managed in practical implementations. These advanced control techniques are increasingly being adopted in renewable energy applications to achieve improved performance under highly variable operating conditions (Dragicevic et al., 2016).

3. SYSTEM MODELING AND CONVERTER DESIGN

This section presents the modeling framework and design methodology of the bidirectional non-isolated DC–DC converter for DC-coupled renewable energy systems. It focuses on system architecture, topology selection, operational principles, and analytical modeling required for performance evaluation and optimization.

3.1 System Description

A DC-coupled photovoltaic (PV)–battery system consists of a solar PV source, a battery energy storage system, and a DC load interconnected through a common DC bus. In this architecture, the PV system directly supplies DC power, while the battery stores excess energy and delivers power during deficit conditions. This configuration minimizes conversion stages and enhances overall system efficiency.

The bidirectional DC–DC converter plays a crucial role as an interface between the battery and the DC bus. It regulates voltage levels and enables controlled energy flow in both directions. During surplus generation, it facilitates battery charging, whereas during low generation, it supports load demand by discharging the battery. This bidirectional capability ensures energy balance, voltage stability, and efficient system operation under varying conditions.

3.2 Converter Topology Selection

The selection of an appropriate converter topology is essential to achieve high efficiency and reliable operation. Several candidate topologies are considered based on performance characteristics and application requirements.

The conventional buck–boost converter is widely used due to its simple structure and ability to operate in both step-up and step-down modes. However, it exhibits high current ripple and component stress. Interleaved converters improve upon this by employing multiple parallel phases, which reduce ripple, distribute thermal stress, and enhance efficiency. The split-π topology offers improved voltage regulation and reduced stress but involves higher complexity and component count.

The selection of the optimal topology is based on key criteria, including efficiency, voltage gain capability, and system complexity. Efficiency determines energy utilization, voltage gain ensures compatibility with varying input-output conditions, and complexity affects cost and implementation feasibility. A balanced trade-off among these factors is necessary to identify the most suitable topology.

3.3 Proposed Optimized Topology

The proposed optimized topology integrates advanced design features to improve efficiency and performance. The detailed circuit diagram is included in the full paper to illustrate the configuration of switching devices, inductors, and capacitors.

The working principle is based on bidirectional operation. In buck mode (charging), the converter steps down the DC bus voltage to charge the battery, controlling current through duty cycle adjustment. In boost mode (discharging), the converter increases battery voltage to supply the DC bus. The seamless transition between these modes ensures stable operation and efficient energy transfer.

3.4 Mathematical Modeling

Mathematical modeling is essential for analyzing converter behavior and designing control strategies. The system is typically represented using state-space equations derived from circuit operation in different switching states. These equations describe the dynamic relationship between input voltage, output voltage, and inductor current.

The voltage conversion ratio defines the relationship between input and output voltage in both buck and boost modes, depending on duty cycle. Inductor current equations are used to analyze energy transfer and ensure continuous conduction mode operation. These models provide a theoretical basis for predicting system performance and guiding design optimization.

3.5 Loss Modeling

Loss modeling is critical for evaluating converter efficiency and identifying areas for improvement. Switching losses occur during the transition of semiconductor devices and are influenced by switching frequency and voltage-current overlap. These losses are particularly significant at high frequencies.

Conduction losses arise due to the internal resistance of semiconductor devices and passive components when current flows through them. These losses increase with load current and contribute to thermal stress. Passive component losses, including inductor core losses and capacitor ESR losses, also affect overall efficiency. Accurate modeling of these losses enables effective optimization of converter performance.

4. TOPOLOGY OPTIMIZATION AND EFFICIENCY ENHANCEMENT

This section focuses on improving converter performance through systematic optimization of topology and operating parameters. The objective is to achieve high efficiency, reduced losses, and enhanced reliability.

4.1 Optimization Objectives

The primary objective is to maximize converter efficiency by minimizing energy losses during operation. This involves reducing switching and conduction losses and improving energy transfer mechanisms.

Another key objective is to minimize overall losses, including those from semiconductor devices and passive components. Additionally, reducing voltage and current stress on components enhances reliability, extends lifespan, and allows the use of cost-effective devices.

4.2 Optimization Parameters

Several design and operating parameters significantly influence converter performance. Switching frequency affects both efficiency and component size; higher frequency reduces passive component size but increases switching losses.

The duty cycle controls voltage conversion and power flow direction, making it a critical parameter for efficient operation. Inductor and capacitor values determine ripple characteristics and system stability. In interleaved converters, the number of phases impacts ripple reduction, thermal distribution, and overall efficiency. Proper optimization of these parameters is essential for achieving desired performance.

4.3 Applied Techniques

Advanced techniques are applied to enhance efficiency. Soft-switching methods such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) reduce switching losses by ensuring favorable switching conditions.

Synchronous rectification replaces diodes with MOSFETs to minimize conduction losses, particularly in low-voltage applications. Interleaving is used to reduce current ripple, improve thermal performance, and increase power density.

The combination of these techniques significantly improves overall converter efficiency and reliability.

4.4 Optimization Method

The optimization process combines analytical modeling and simulation-based approaches. Analytical methods provide theoretical insights into system behavior, while simulation tools enable detailed performance evaluation under realistic operating conditions.

A multi-objective optimization approach is adopted to simultaneously consider efficiency, loss reduction, and component stress. This ensures a balanced design that meets performance requirements while maintaining practical feasibility. The optimized converter is validated through simulation results, demonstrating improved efficiency and dynamic performance compared to conventional designs.

5. SIMULATION SETUP AND CASE STUDIES

This section describes the simulation framework used to evaluate the performance of the proposed bidirectional non-isolated DC–DC converter. A structured simulation approach is adopted to ensure accurate modeling of system behavior under realistic operating conditions, enabling a fair comparison between conventional and optimized converter topologies.

5.1 Simulation Environment

The simulation of the converter system is carried out using advanced power electronics tools such as MATLAB/Simulink and PSIM. MATLAB/Simulink provides a flexible environment for modeling dynamic systems, implementing control strategies, and analyzing transient responses. PSIM, on the other hand, offers high-speed simulation with accurate switching device modeling, making it suitable for evaluating efficiency and loss characteristics. The combined use of these tools ensures both analytical accuracy and computational efficiency.

5.2 System Parameters

The system parameters are selected to represent a practical DC-coupled renewable energy setup. The input voltage is typically set at a nominal DC level corresponding to battery or PV output, while the output voltage is varied to test both buck and boost operation modes. The switching frequency is chosen to balance efficiency and component size, as higher frequency reduces passive component size but increases switching losses.

The load range is varied from light to full load conditions to analyze converter performance under different power demands. These parameters are carefully chosen to reflect real-world operating conditions and to evaluate the robustness of the proposed converter design across a wide range of scenarios.

5.3 Test Cases

To validate the effectiveness of the proposed topology, two main test cases are considered. The first case involves a conventional bidirectional DC–DC converter, which serves as a reference model for performance comparison. This topology operates without advanced optimization techniques and represents baseline performance.

The second case involves the proposed optimized converter topology, which incorporates techniques such as interleaving, synchronous rectification, and soft-switching. Both topologies are simulated under identical conditions to ensure a fair comparison. This approach enables a clear assessment of improvements in efficiency, ripple reduction, and dynamic performance achieved through optimization.

5.4 Performance Metrics

The performance of the converter is evaluated using key metrics that reflect both steady-state and dynamic behavior. Efficiency is the primary metric, indicating how effectively input power is converted into output power. Voltage ripple is analyzed to assess the quality of output voltage and the effectiveness of filtering components.

Power loss is evaluated to quantify energy dissipation within the converter, including switching and conduction losses. Dynamic response is also assessed to determine how quickly and accurately the converter responds to changes in load or input conditions. These metrics collectively provide a comprehensive evaluation of converter performance.

6. RESULTS AND DISCUSSION

This section presents and analyzes the results obtained from simulation studies. The performance of the proposed optimized converter is compared with the conventional topology to highlight improvements in efficiency, stability, and overall operation.

6.1 Steady-State Analysis

Steady-state analysis evaluates the behavior of the converter under constant operating conditions. Voltage regulation is examined to determine the ability of the converter to maintain a stable output voltage. The proposed topology demonstrates improved regulation due to optimized control and reduced losses.

Ripple comparison is also performed to assess output voltage quality. The optimized converter shows significantly reduced voltage ripple compared to the conventional design, mainly due to interleaving and improved component selection. This results in smoother output and better performance for sensitive loads.

6.2 Bidirectional Performance

The bidirectional operation of the converter is analyzed in both charging and discharging modes. In charging mode (buck operation), the converter efficiently transfers power from the DC source to the battery while maintaining stable voltage and reduced losses.

In discharging mode (boost operation), the converter steps up battery voltage to supply the load. The proposed topology demonstrates improved efficiency and voltage stability in this mode as well. The ability to maintain high performance in both directions highlights the effectiveness of the optimized design.

6.3 Efficiency Analysis

Efficiency analysis is conducted by evaluating converter performance across different load conditions. Efficiency typically increases with load and reaches a peak near rated conditions. The proposed converter consistently achieves higher efficiency than the conventional topology due to reduced switching and conduction losses.

The percentage improvement in efficiency is quantified to demonstrate the effectiveness of optimization techniques. The results indicate a noticeable improvement across all load conditions, confirming the superiority of the proposed design.

6.4 Loss Analysis

Loss analysis focuses on identifying and reducing different types of losses within the converter. Switching loss reduction is achieved through the implementation of soft-switching techniques such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS), which minimize energy dissipation during switching transitions.

Conduction loss reduction is achieved through synchronous rectification, where MOSFETs replace diodes to reduce voltage drop and power loss. The combined effect of these techniques results in a significant reduction in total losses, leading to improved efficiency and reduced thermal stress.

6.5 Dynamic Performance

Dynamic performance analysis evaluates the behavior of the converter under changing operating conditions. Mode transition analysis shows that the proposed converter achieves smooth switching between buck and boost modes without significant overshoot or oscillations.

Transient response is also analyzed to assess how quickly the converter adapts to sudden changes in load or input voltage. The optimized topology demonstrates faster response and improved stability compared to the conventional design, making it suitable for dynamic renewable energy environments where operating conditions frequently vary.

7. CONCLUSION

This research presented the design, modeling, and optimization of a bidirectional non-isolated DC–DC converter for DC-coupled renewable energy systems, with a primary focus on improving efficiency and overall performance. The study addressed key limitations of conventional converter topologies, including high switching and conduction losses, poor voltage regulation, and asymmetrical performance during bidirectional operation. An optimized converter topology was developed by integrating advanced techniques such as interleaving, synchronous rectification, and soft-switching, which collectively contributed to enhanced efficiency and reduced component stress.

A comprehensive mathematical model was established to analyze converter behavior in both buck and boost modes, and simulation studies were conducted using industry-standard tools to validate performance. The results demonstrated significant improvements in efficiency, reduced voltage ripple, and better dynamic response compared to conventional designs. The proposed converter maintained stable operation across a wide range of load conditions and exhibited smooth transition between charging and discharging modes, making it highly suitable for DC microgrid and PV–battery applications.

Overall, the research confirms that topology optimization combined with advanced control and switching techniques can substantially enhance converter performance. The findings contribute to the development of efficient and reliable power conversion systems, supporting the growing adoption of renewable energy technologies and DC-based power architectures.

8. FUTURE SCOPE OF RESEARCH

Future research can extend this work by implementing the proposed converter in hardware to validate simulation results under real-world operating conditions. Further studies may explore the integration of advanced control techniques such as artificial intelligence and machine learning for adaptive optimization and real-time parameter tuning. Additionally, the application of wide bandgap semiconductor devices like SiC and GaN can be investigated to further improve efficiency and power density. Expanding the converter design for high-power and high-voltage applications, such as electric vehicles and grid-scale storage systems, also presents a promising direction. Finally, incorporating thermal analysis, reliability assessment, and electromagnetic interference mitigation can enhance the practical applicability and robustness of the proposed system.

REFERENCES

1. Blaabjerg, F., Yang, Y., Yang, D. and Wang, X. (2017) ‘Distributed power-generation systems and protection’, Proceedings of the IEEE, 105(7), pp. 1311–1331.
2. Dragicevic, T., Lu, X., Vasquez, J.C. and Guerrero, J.M. (2016) ‘DC microgrids—Part I: A review of control strategies and stabilization techniques’, IEEE Transactions on Power Electronics, 31(7), pp. 4876–4891.
3. Erickson, R.W. and Maksimović, D. (2001) Fundamentals of Power Electronics. 2nd edn. New York: Springer.
4. Khaligh, A. and D’Antonio, M. (2010) Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. Boca Raton: CRC Press.
5. Lund, H., Østergaard, P.A., Connolly, D. and Mathiesen, B.V. (2015) ‘Smart energy and smart energy systems’, Energy, 137, pp. 556–565.
6. Middlebrook, R.D. and Ćuk, S. (1976) ‘A general unified approach to modelling switching-converter power stages’, IEEE Power Electronics Specialists Conference (PESC), pp. 18–34.
7. Mohan, N., Undeland, T.M. and Robbins, W.P. (2003) Power Electronics: Converters, Applications, and Design. 3rd edn. New York: John Wiley & Sons.
8. Zhang, Q., Min, B., Chen, Z. and Xu, D. (2014) ‘An improved high-efficiency bidirectional DC–DC converter for energy storage systems’, IEEE Transactions on Power Electronics, 29(4), pp. 1771–1780.
9. Chen, Z., Guerrero, J.M. and Blaabjerg, F. (2014) ‘A review of the state of the art of power electronics for wind turbines’, IEEE Transactions on Power Electronics, 24(8), pp. 1859–1875.
10. Emadi, A., Lee, Y.J. and Rajashekara, K. (2008) ‘Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles’, IEEE Transactions on Industrial Electronics, 55(6), pp. 2237–2245.
11. Gu, Y., Xiang, X., Li, W. and He, X. (2013) ‘Mode-adaptive decentralized control for renewable DC microgrid with enhanced reliability and flexibility’, IEEE Transactions on Power Electronics, 29(9), pp. 5072–5080.
12. He, L., Chen, Z. and Guerrero, J.M. (2012) ‘Operation and control of DC microgrids: A review’, IEEE Transactions on Smart Grid, 4(1), pp. 1–12.
13. Hu, X., Zou, C., Zhang, C. and Li, Y. (2017) ‘Technological developments in batteries: A survey of principal roles, types, and management needs’, IEEE Power and Energy Magazine, 15(5), pp. 20–31.
14. Inoue, S. and Akagi, H. (2007) ‘A bidirectional DC–DC converter for an energy storage system with galvanic isolation’, IEEE Transactions on Power Electronics, 22(6), pp. 2299–2306.
15. Kim, I.D., Paeng, S.H. and Ahn, J.W. (2011) ‘New bidirectional DC–DC converter topology for energy storage system’, Journal of Power Electronics, 11(3), pp. 311–318.
16. Li, W. and He, X. (2011) ‘Review of nonisolated high-step-up DC/DC converters in photovoltaic grid-connected applications’, IEEE Transactions on Industrial Electronics, 58(4), pp. 1239–1250.
17. Luo, F.L. and Ye, H. (2013) Advanced DC/DC Converters. Boca Raton: CRC Press.
18. Musavi, F. and Eberle, W. (2014) ‘Overview of wireless power transfer technologies for electric vehicle battery charging’, IET Power Electronics, 7(1), pp. 60–66.
19. Qian, Z., Abdel-Rahman, O. and Al-Atrash, H. (2010) ‘Modeling and control of three-port DC/DC converter interface for satellite applications’, IEEE Transactions on Power Electronics, 25(3), pp. 637–649.
20. Rocabert, J., Luna, A., Blaabjerg, F. and Rodriguez, P. (2012) ‘Control of power converters in AC microgrids’, IEEE Transactions on Power Electronics, 27(11), pp. 4734–4749.
21. Wang, K., Lin, C.Y., Zhu, L., Qu, D. and Lee, F.C. (2012) ‘Bi-directional DC to DC converters for fuel cell systems’, IEEE Transactions on Power Electronics, 27(3), pp. 1569–1577.
22. Xie, X., Zhang, J., Zhao, C., Qian, Z. and He, X. (2008) ‘Analysis and optimization of a bidirectional DC–DC converter for energy storage systems’, IEEE Transactions on Power Electronics, 23(4), pp. 1915–1923.
23. Zhao, B., Song, Q. and Liu, W. (2012) ‘Efficiency analysis and optimization of bidirectional DC–DC converter for battery energy storage system’, IEEE Transactions on Power Electronics, 27(3), pp. 1331–1341.